LINK PERFORMANCE ANALYSIS FOR A PROPOSED FUTURE ARCHITECTURE OF THE AIR FORCE SATELLITE CONTROL NETWORK

THESIS

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Abstract

The Air Force Satellite Control Network (AFSCN) is a worldwide network of ground stations that support a wide variety of users from the National Aeronautics and Space Administration (NASA) to the National Reconnaissance Office (NRO). The network performs tracking, telemetry, and commanding (TT&C) for these varied users. Users, located at Satellite Operations Centers (SOC), must compete for time on the AFSCN. This thesis demonstrates how to predict satellite link performance, specifically by users of the AFSCN. It will also demonstrate how users might use this capability to save spacecraft power. A tool was created called the AFSCN Link Predictor (LP) which predicts BER across a future contact. The design of the AFSCN LP and a proposed modification to the AFSCN using DoD Architecture Framework (DoDAF) was accomplished. A simulation, using this tool, was conducted that demonstrates the utility of performance prediction for representative low, medium, and high earth orbiting spacecraft communicating with two geographically separated ground stations.

Acknowledgments

I thank Bruno Calanche for his invaluable direction and patience as he helped me tackle the many tough challenges that this research presented. I thank Dr. Colombi for providing the much needed focus throughout this process and for providing the perspective to help make my effort relevant.

Eric W. Nelson

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I. Introduction

Background

The Air Force Satellite Control Network (AFSCN) operates ground stations that perform Tracking, Telemetry, and Commanding (TT&C) for various DoD spacecrafts, providing uplink and downlink capability for many users. One value that determines the success of an uplink or downlink (i.e. support or pass), is the signal to noise ratio (SNR). SNR is the power of the transmitted signal over the noise power. Both uplink and downlink require minimum signal to noise ratio (SNR) to be considered successful. If the minimum SNR is not met, the data cannot be extracted from the signal.

Currently, the users do not know what the SNR performance will be over a given contact because there is currently no SNR prediction capability in the AFSCN. The spacecraft operators, or users, schedule time on the AFSCN with no regard to the estimated SNR. This presents an issue. With no way to estimate or predict the performance (i.e., SNR) of an upcoming support, the users cannot accurately request time on the network because they do not have a quantitative representation of the estimated performance of the contact. If the users had an estimate of how the link would perform, they would be better prepared schedule contacts more efficiently.

SNR is largely dependent on the signal power from the transmitter. With the ability to predict the SNR of a downlink, the users would be able to optimize the power level to the amount required to achieve the desired SNR. This is a huge advantage as power consumption is an important factor in spacecraft operations. This could be attractive within the current Defense budget environment, as fewer new (replacement) systems may be affordable.

There are apparent advantages to predicting link performance. So why doesn't the AFSCN have this capability? During the design phase of spacecraft programs, a worst case link budget is used. In other words, the spacecraft is designed to obtain the needed SNR in worst case scenarios (e.g., high noise environments). Therefore, varying SNR is not normally considered an important issue because the needed performance can be obtained in most conditions. As a result, there is no SNR predictive capability within the AFSCN.

This thesis will present how and where performance prediction might be introduced into the AFSCN. First, the current architecture of the AFSCN will be analyzed with regards to operational nodes and the needed data/information flows between them.. Next, the physics and models needed to predict uplink and downlink SNR will be defined and discussed. To automate the SNR calculations a tool was created by the author called the AFSCN Link Predictor (AFSCN LP). The internal architecture of this tool will be defined and discussed. With the inputs, outputs, mechanisms, and controls (ICOMs) of the AFSCN LP defined, a proposed AFSCN architecture modification will be explored. To illustrate the utility of the AFSCN LP, simulations of representative spacecraft contacts will be conducted and analyzed.

Opportunity Statement

Currently, the AFSCN does not perform link performance prediction. Without link prediction, it is impossible to know how a scheduled spacecraft link will perform. Currently the AFSCN and the DoD are able to meet spacecraft users' needs without this capability, but efficiencies could be realized with its implementation.

Investigative Questions

The hypothesis for this research is that link performance prediction would benefit the AFSCN and its users and that this capability can be successfully introduced into the architecture of the AFSCN. Having SNR prediction capability would allow the spacecraft operators to more accurately predict the amount of time needed for a support and potentially result in power savings for the spacecraft. Guiding the research are the following questions:

How can link performance be predicted?

Where in the current AFSCN architecture would performance prediction be applied?

Lastly,

How would the AFSCN and its users benefit from link prediction capability?

Methodology

An AFSCN LP was created which integrates several physics-based models of antennae patterns, thermal noise and signal gains. The internal architecture of this product will be discussed. A proposed AFSCN architecture modification incorporating this capability will be recommended. Finally, to demonstrate the utility of this capability, AFSCN LP simulations will be analyzed.

Implications

If the users of the AFSCN had a performance prediction capability, they would better understand the future performance of their scheduled contacts and would be better prepared to schedule time on the AFSCN more efficiently. As stated previously, SNR is largely dependent on the signal power from the transmitter. With the ability to predict the SNR of a downlink, the users would be able to optimize the power level to the amount required to achieve the desired SNR. This is a huge advantage as power consumption is an important factor in spacecraft operations.

II. Literature Review

Background Summary

This chapter discusses the importance of the signal to noise ratio in spacecraft links, the current AFSCN architecture, and currently available link performance prediction software tools.

What is SNR and why is it important?

SNR normally refers to the carrier power over the noise power spectral density. This value is important because it is needed to determine the Bit Error rate (BER) of the subcarriers. The subcarriers are what contain the data needed by the users. BER refers to the number of errors over the number of bits transmitted. Certain types of data require that the BER not be above a certain threshold. Therefore, the SNR is important because it is directly linked to BER. By knowing the predicted BER or SNR of their respective links, the users then know, within a margin of error, what the performance of that link will be and when/how long they should schedule their AFSCN support and/ or how much power to expend.

Current AFSCN architecture

To understand where link performance prediction capability might fit in the architecture of the AFSCN, it is important to understand the current architecture using DoD Architecture Framework (DoDAF) of the AFSCN. As can be seen from the Operational Concept Diagram (OV-1) in Figure 1, the AFSCN supports a wide variety of users. Each one of these users requires telemetry, tracking, and commanding (TT&C) support from the AFSCN.

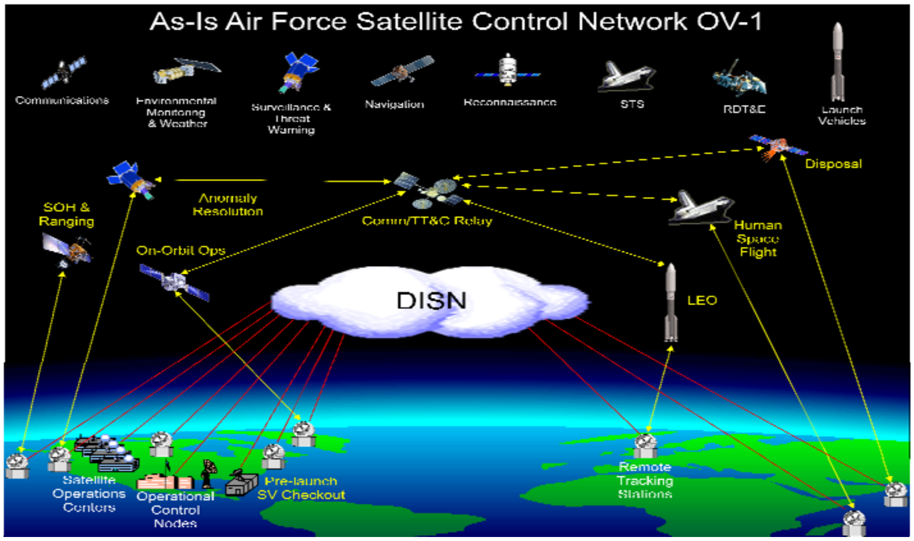

Figure 1 - AFSCN Concept of Operations (OV-1)

The users are composed primarily of spacecraft operations centers (SOC) and external users supporting communication services, navigation, surveillance, reconnaissance, environmental/weather, research and development and launch. From the OV-2 (Figure 2) it can be seen that both of these users must interface with the Network operations center (NOC) to request support from the AFSCN. The NOC is responsible for de-conflicting requests and disseminating the Network Tasking Order (NTO) to all of the users and Remote Tracking Stations (RTS), or ground stations. The NTO tells the network when each spacecraft will be supported at each RTS.

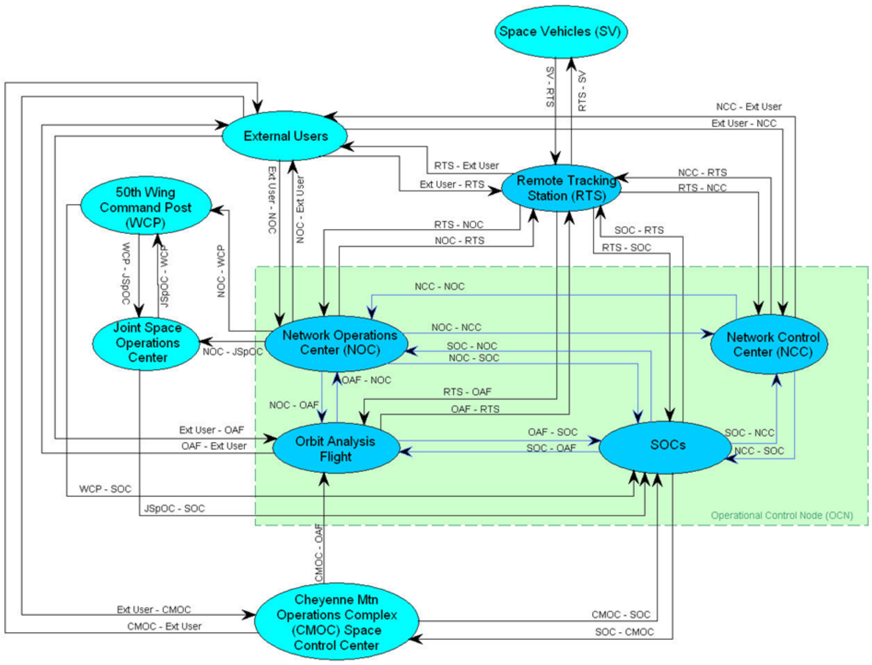

Figure 2 - AFSCN Operational Node Connectivity (OV-2)

The (Ext User–NOC) and (SOC–NOC) resource flows from the OV-2 are where the users request support from the AFSCN. Historically in DoDAF, these exchanges were called need lines. These need lines are further defined in the OV-3. An excerpt from the AFSCN OV-3 is shown in Table 1.

Table 1 – AFSCN Resource (Information) Flow Matrix OV-3

Need Line	Information Exchange	Source Activity	Destination Activity	Content
SOC - NOC	Program Action Plan (PAP)	Prepare Contact Support Plan Determine Support Requirements Submit Daily PAP	Collect Scheduling Requests for Flight Activities Optimize Schedule and Identify Conflicts	task start time, duration, turnaround time, equipmt reqd, RTS site/side, function, Automated remote Tracking Station (ARTS) config

Ext User - NOC	Program Action Plan (PAP)	Prepare Contact Support Plan Determine Support Requirements Submit Daily PAP	Collect Scheduling Requests for Flight Activities Optimize Schedule and Identify Conflicts	task start time, duration, turnaround time, equipmt reqd, RTS site/side, function, ARTS config
OAF-SOC	Predictive Radio Frequency Interference (RFI) reports	Submit Predictive RFI	Receive Predictive RFI Reports	time and duration of conflict, conflicting frequency, and SV separation data
OAF-Ext User	Predictive Radio Frequency Interference (RFI) reports	Submit Predictive RFI	Receive Predictive RFI Reports	time and duration of conflict, conflicting frequency, and SV separation data

Based on the OV-2 and the description of the needlines in the OV-3, link performance prediction is not generated. The Orbital Analysis Flight (OAF) shown in the OV-2 does, however, submit predictive RFI reports. It includes only basic information such as the time, duration, and frequency of the interference.

The content of these two need lines is what is of concern. As can be seen from this OV-3 the users are required to submit a start time and duration. Here the SOC requests use of a particular RTS for a specified period time. This requested start time and duration is not based on quantitative predicted performance of the link.

It is a common occurrence in the AFSCN that the users request more time than needed and the support is cut short. This results in wasted time on the Network that could be used for another support. By predicting the link performance of every support, the users would have the capability of predicting the duration needed for their support thus allowing the network to be available for more requests. Minutes or seconds saved for each support would add up across the network vastly increasing the efficiency of the AFSCN.

Current link prediction tools

There are link prediction products currently available. These products utilize the same functionality required by the AFSCN but are not tailored specifically to it. Two of the tools use physics-based models and MATLAB to predict performance. The other tool proposes using a method called soft computing to predict performance.

Dynamic link analysis tool

The Dynamic Link Analysis (DLA) tool was developed by Mr. Yogi Krikorian. It is a MATLAB based tool that was designed to predict link performance during launches on the Eastern and Western Launch ranges operated by the US Air Force. This tool provides the user with a Graphical User Interface (GUI) that is shown in Figure 3.

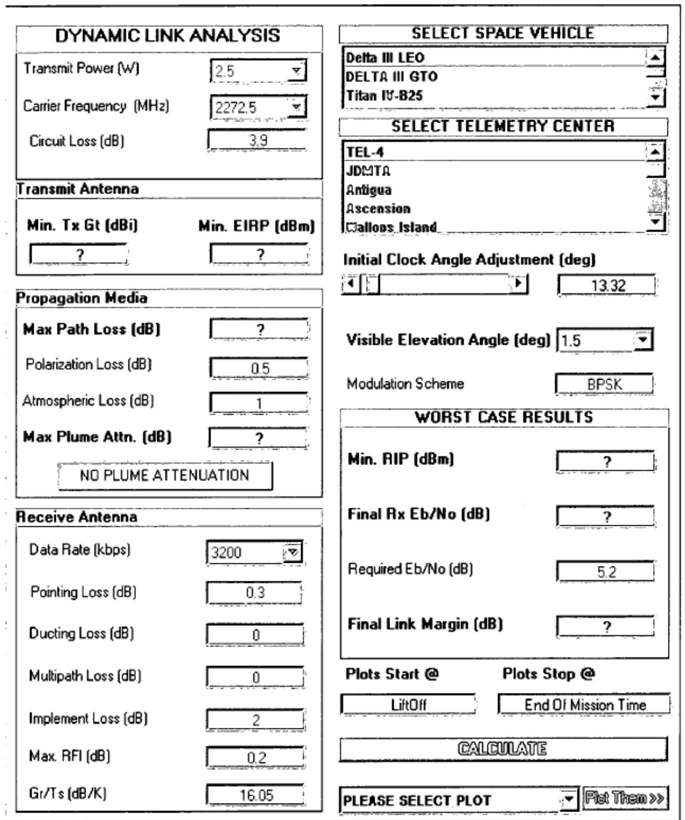

Figure 3 – Dynamic Link Analysis (DLA) Graphical User Interface (GUI)

As can be seen from Figure 3, the DLA GUI allows a user to select the space vehicle and earth station desired. This tool then predicts the performance of the link based on known parameters. These selections then translate into a predicted SNR. There is no doubt that this tool is very valuable to the AF because a launch is a very expensive effort and all variables must be fully understood. Most link analysis is static which means it assumes constant performance throughout the contact based on worst case performance. This tool performs dynamic link analysis that determines link performance at specified intervals (Krikorian, 2003).

Telecom forecaster

The second tool is the Telecom Forecaster Predictor. It uses a similar GUI to the one used by the DLA tool (Tung & Tong, 1999). The objective of this tool was to standardize deep space communications analysis throughout the Jet Propulsion Laboratory. This tool predicts the SNR vs. time for various uplink and downlink configurations. This tool is also MATLAB based.

Soft computing

Soft computing is an interesting approach to link performance prediction. A paper was authored by the Global Educational Network for Spacecraft Operations (GENSO) and its purpose was to introduce a possible technique to predict the needed length of contacts thus making more time available to all users. GENSO is a conglomerate of multiple ground stations shared by educational organizations most of which need access to LEO spacecraft. As with any LEO spacecraft, access time is limited. Taking advantage of every second is important. This approach would gather as many variables as possible that relate to the quality of the communications link and then correlate them to link quality through machine learning (Preindl, Mehnen, Rattay, & Nielsen, 2009). This is very different than the previously mentioned tools. It does not use physics-based models, but relies only on empirical interdependencies to predict performance. This data mining approach would continuously update a database with new variables and search for more interdependencies becoming more and more accurate at prediction. This approach might be useful but is not proven and will not be considered by the author.

III. Methodology

Chapter overview

This chapter first discusses how link performance is defined and computed. Then those calculations will be used to create a software program called the Air Force Satellite Control Network link Predictor (AFSCN LP) that computes link performance. The architecture of this tool will be illustrated and discussed. With information flows introduced in Chapter 2, a proposed modification to the AFSCN architecture will be presented.

Link performance calculations

When link performance is discussed, signal to noise ratio (SNR) is the common measure of performance. This is also known as the ratio of the received carrier power to the noise power spectral density. In the next sections it will be explained how the SNR is calculated. It should be noted that the performance calculations that follow are specific to the AFSCN Remote Tracking Station Block Change (RBC) configuration and the Space to Ground Link Subsystem (SGLS) waveform.

Signal to noise ratio

The equation for the SNR is given below (Maral and Bousquet, 2006).

$$(C/No) = (EIRP)_T(1/L)(G/T)_R(1/k) \tag{1}$$

where,

EIRP is the Effective Isotropic Radiated Power,

L is the medium losses,

G/T is the receiving antenna gain over the noise temperature, and

k is Boltzmann's constant (1.3806×10^{-23} J/K or -228.5991 dBW/K/Hz).

The generic Equation 1 can be applied to both uplink and downlink. $(EIRP)_T$ is the EIRP of the transmitting antenna and $(G/T)_R$ is the G/T of the receiving antenna. During uplink, for example, the earth station (ES) would be considered transmitting so its EIRP would be needed in the SNR calculations. Also, the G/T of the receiving spacecraft (SC) would be referenced for the uplink SNR calculation. These factors will be explained further in the following sections. Figure 4 illustrates how these variables are related.

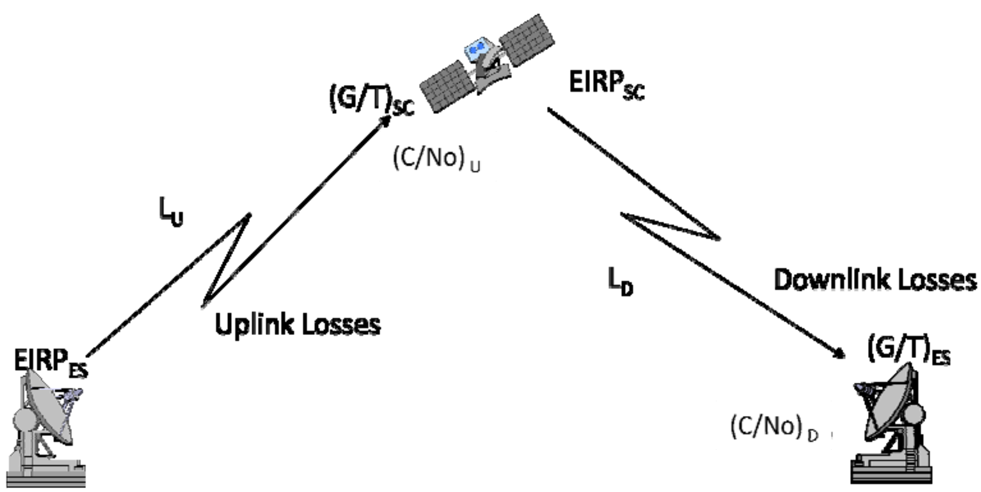

Figure 4 – Spacecraft Uplink/Downlink

Effective Isotropic Radiated Power (EIRP)

The EIRP is the product of a transmitting antenna's gain and the radiated power.

The equation for EIRP is:

$$EIRP = G_T P_T \tag{2}$$

where,

G_T is the Gain of the antenna and

P_T (mW) is the radiated power.

The radiated power is determined by the user and the gain is calculated by knowing the size/shape of the antenna, the efficiency of the antenna, and the frequency of the radiated electromagnetic wave.

Uplink EIRP

During uplink, the RBC antenna transmits the signal and therefore it supplies the EIRP. To compute the EIRP, the gain is needed. The RBC antenna has a circular aperture. For antennae with a circular aperture, the gain is given below (Maral and Bousquet, 2006).

$$G = \eta(\pi D f/c)^{\wedge 2} \tag{3}$$

where,

η is the antenna efficiency,

D (m) is the diameter of the antenna,

f (1/s) is the frequency of the electromagnetic wave, and

c (m/s) is the speed of light.

For the RBC antenna the efficiency, η, is assumed to be 0.668 and the diameter is set at 13 meters. The frequency, however, will depend on the particular link configuration.

Downlink EIRP

During downlink the spacecraft will transmit the signal. For the purposes of the AFSCN LP, the spacecraft antenna is assumed to be an Omni-directional antenna. An

Omni antenna is stationary and normally used on low earth orbiting spacecrafts (LEOs). An Omni antenna gain model was used from the Telecom Forecaster. The model is based on the degrees off boresight (DOFF) and is given below (Tung & Tong, 1999)

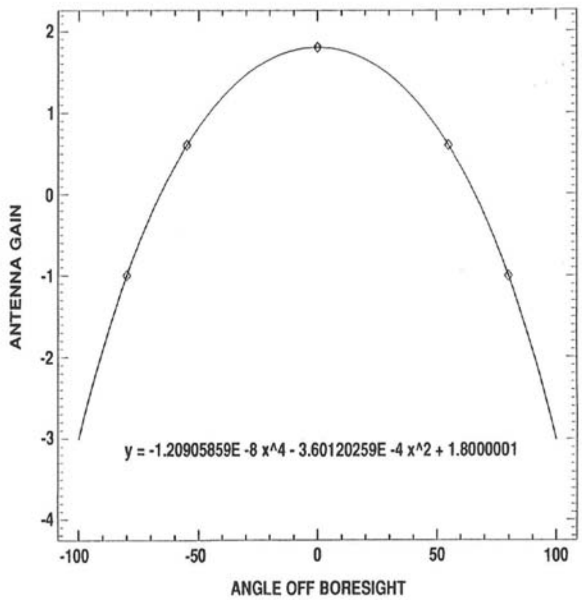

Figure 5 – Omni Gain Model

To compute the EIRP the power is also needed. The power is set as an adjustable variable in the AFSCN LP. With the selected power and the gain model the downlink EIRP can be determined using the EIRP equation defined previously.

Noise temperature

The noise temperature is all of the power added to the carrier from environmental and man-made sources. This added noise makes it difficult for the receiver to distinguish between the noise and the desired signal. Noise comes from natural sources like the earth and sun. It is also radiated from the receiving equipment which imparts additional gain but also additional noise. Each stage in the signal processing process imparts a gain and/or additional noise.

Downlink system noise temperature

The total system noise temperature for downlink was calculated using the model below which is a linear combination of environmental factors and antenna effects.

$$T_S = T_R + \alpha\,(T_1 + T_2 e^{-a\theta} + (255 + 25CD)[\,1 - (\,1/(A_{ZEN}/10^{10\sin\theta})]\,) + (1-\alpha)T_O \ \text{(K)} \quad (4)$$

where,

T_R (K) is the noise from the transmission medium from the antenna to the electronics otherwise known as the feeder,

T_O (K) is the ambient temperature of the earth station,

α is a parameter specific to the ground station antenna,

θ (deg) is the elevation angle,

T_1, T_2, (K) and a are system specific parameters,

CD is a coefficient that models the current weather conditions, and

A_{ZEN} is the atmospheric attenuation based on the CD weather conditions.

The values for the above values were determined for the RBC. This model was created for the RBC system. T_R and T_O are constants. The Deep Space Network Telecommunications Link Design Handbook 810-005 system noise temperature model was used (810-005, 2000) and then calibrated for use on the AFSCN RBC system. Table 2 from the Handbook shows the atmospheric attenuation effects.

Table 2 - S-Band Atmospheric Attenuation

Weather Condition	A_{ZEN}, dB*		
	DSS 16	DSS 46	DSS 66
Vacuum	0.000	0.000	0.000
CD = 0.00	0.033	0.036	0.034
CD = 0.50	0.032	0.035	0.033
CD = 0.90	0.031	0.034	0.033

Figure 6 illustrates the correlation between antenna noise temperature and elevation angle. As the elevation angle approaches 90 degrees the noise temperature decreases.

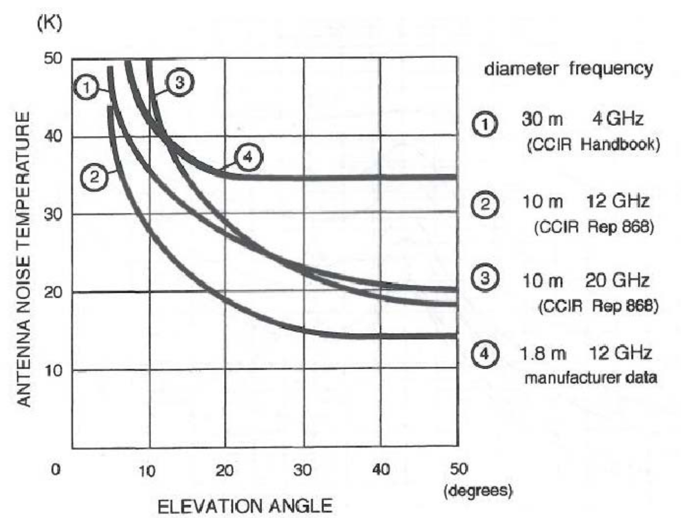

Figure 6 - Ambient Noise Temperature vs. Elevation (Maral and Bousquet, 2006)

Uplink system noise temperature

For the uplink, the noise temperature sources mainly come from the Earth. The system noise temperature model from the Telecom Forecaster was used to model the uplink system noise temperature (Equation 5).

$$T_S = (T_A + (F\text{-}1)T_O)G \tag{5}$$

where,

T_S (K) is the system noise temperature,

T_A (K) is the antenna noise temperature,

F (dimensionless) is the noise figure of the spacecraft,

G is the gain of the spacecraft, and

To (K) is the ambient temperature of the antenna.

Signal losses

The final factor needed to determine the AFSCN link SNR are the losses. There are multiple sources of loss that will be considered.

Pointing error loss

The pointing error loss is caused from imperfect alignment of the transmitting and receiving antennas. The pointing loss model from the Telecom Forecaster will be used and is shown below (Tung & Tong, 1999)

$$L_P = 3[2(DOFF) / HPBW]^2 \tag{6}$$

where,

$DOFF$ (deg) is the degrees offset from boresight and

$HPBW$ (deg) is the half power beam width.

The HPBW references the angle between the directions in which the gain falls to half of its maximum value.

Free space loss

Further signal loss is caused by what is referred to as free space, or path, loss. This source of loss is applicable to uplink and downlink. Free space loss is determined by the signal frequency f and the range from the spacecraft to the earth station. As an electromagnetic signal propagates through space it spreads out losing its power along the way. The equation for path loss is given in Equation 7.

$$L_{FS} = (4\pi R\, f/c)^2 \qquad (7)$$

where,

R (m) is the distance, or range, of the spacecraft to the earth station and

c (m/s) is the speed of light.

Polarization loss

Polarization loss occurs when the receiving antenna is not aligned with the polarization of the received wave. For example, with a circular polarized wave the polarization takes place along the axis of the transmitting antenna. If the receiving antenna axis is not aligned with the transmitting antenna then elliptical polarization is seen at the receiving antenna (Maral & Bousquet, 2006). This results in a signal loss. The polarization loss model from the Telecom Forecaster was used and is shown in Figure 9 and Equation 8 below. This loss model is degrees off boresight dependent and assumes the spacecraft utilizes an Omni antenna.

$$L_{Pol} = 1.389*10^8(DOFF^4) - 3.389*10^4(DOFF^2) - 2.86*10^7 \text{ (dB)} \qquad (8)$$

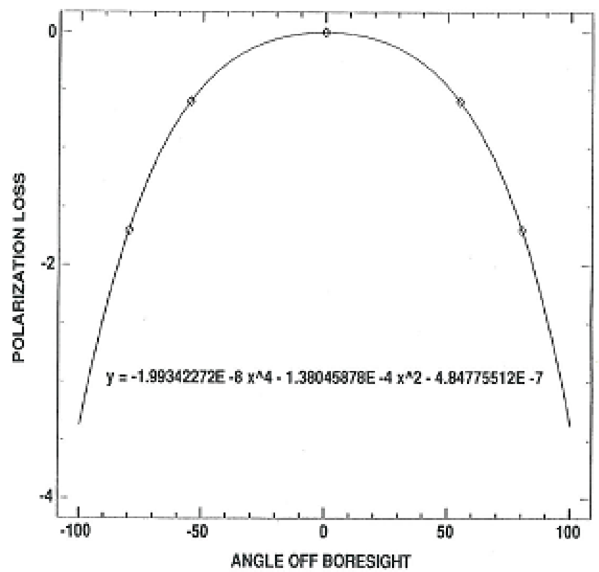

Figure 7 - Telecom Forecaster Polarization Loss Model

Uplink performance

Now with the SNR equation defined, the uplink performance can be calculated. The SNR equation for uplink is given below.

$$(C/No)_U = (EIRP)_{ES}(1/L_U)(G/T)_{SC}(1/k) \tag{9}$$

where,

L_U (dB) comprises the combined uplink losses and

k is the Boltzmann's constant.

With both the signal losses and the system noise temperature varying it is apparent that the link performance will vary throughout a contact.

Downlink performance

The SNR for downlink is given below.

$$(C/No)_D = (EIRP)_{SC}(1/L_D)(G/T)_{ES}(1/k) \tag{10}$$

where,

L_D (dB)comprises the combined downlink losses and

k is the Boltzmann's constant.

The system noise temperature for downlink will vary over time for all spacecraft contacts. This will yield different system performance at each interval of the contact. This fluctuation in noise temperature will be less pronounced for geostationary or geosynchronous orbits because they remain more or less stationary with respect to the spacecraft. However, the noise temperature will vary greatly for LEO orbits because of the system noise temperature's dependence on elevation.

Energy per bit over noise density (Eb/No)

Now that the SNR of the carrier wave is known, the energy per bit over noise power density, or Eb/No, of the subcarrier can be calculated. There can be multiple subcarriers within a signal. For SGLS downlink, these are normally composed of a ranging and telemetry data subcarrier. The AFSCN LP only computes the telemetry subcarrier Eb/No. To compute the Eb/No there are a losses that need to be taken into account: the service modulation loss and a loss associate with the data rate. The process of modulation takes power from the carrier and distributes it to the subcarriers. Equation 11 yields the modulation loss given a specified modulation index (MI) (TOR-2011(1571)-2, 2011).

$$\textit{Service mod loss} = 10*Log_{10}\,(2*bessel(1,MI)^{\,2}) \qquad (11)$$

where, *bessel()* represents the Bessel function of the first order.

There is also a loss associated with the data rate. If the data rate is increased the signal loss is increased. The loss associated with the data rate of the telemetry subcarrier is determined by the simple equation below.

$$Data\ rate\ loss = 10*Log_{10}\ (Data\ rate) \quad (12)$$

With the equation for the C/No known and the two previous losses defined, the equation to determine Eb/No of the telemetry subcarrier is given below (TOR-2011(1571)-2, 2011).

$$TLM\_Eb/No = (C/No)_D - Service\ mod\ loss - Data\ rate\ loss \quad (13)$$

Bit error rate

In spacecraft communications, the Bit error rate (BER) is an important value. It represents the performance of the subcarrier. The theoretical BER performance of the telemetry subcarrier is given by the equation below assuming SGLS waveform (AFSCN, 2004).

$$\text{BER} = 0.5\ erfc(\sqrt{TLM\_EbNo}) \quad (14)$$

where,

erfc is the complimentary error function and

TLM_EbNo (dB) is the telemetry subcarrier energy per bit over noise density.

Link Geometry

To determine the link geometry, Analytical Graphics, Inc's (STK) space systems modeling application will be used to generate geometric arrays for each link. The three parameters used to predict the performance of each link are: elevation angle, degrees off-boresight, and range. The ground stations are selected from the online database provided by STK and generic spacecraft orbits were defined using STK's orbit modeler. STK automatically generates time based arrays of any orbital location parameter given a ground station location, spacecraft location and orbit, and support start and end times. This orbital information is then exported from STK and imported into MATLAB and available to use in the AFSCN LP. Representative low earth (LEO), medium earth (MEO), and high earth (HEO) orbits were modeled using STK. Given a ground station STK will determine its availability to a particular spacecraft. Figures 8 and 9 are STK illustrate the orbits modeled. The availability of these orbits to Colorado Tracking Station (CTS) and Diego Garcia Tracking Station (DGS) were modeled.

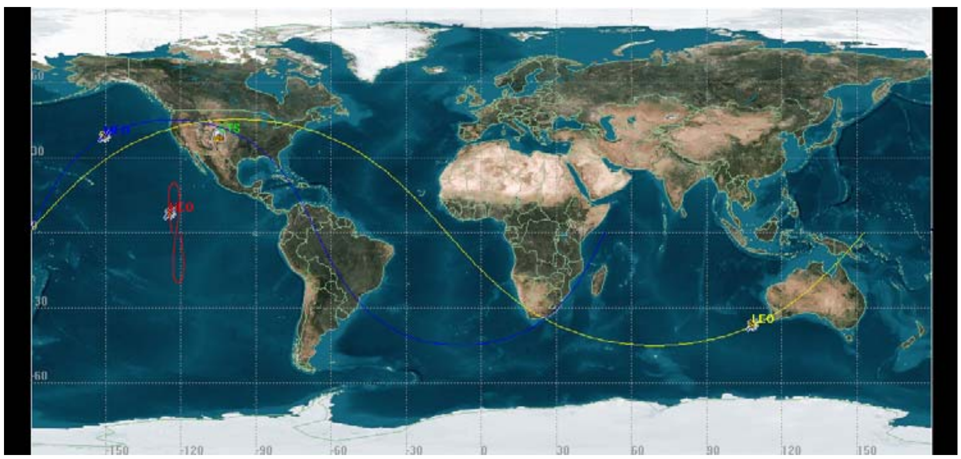

Figure 8 - Colorado Tracking Station STK Scenario

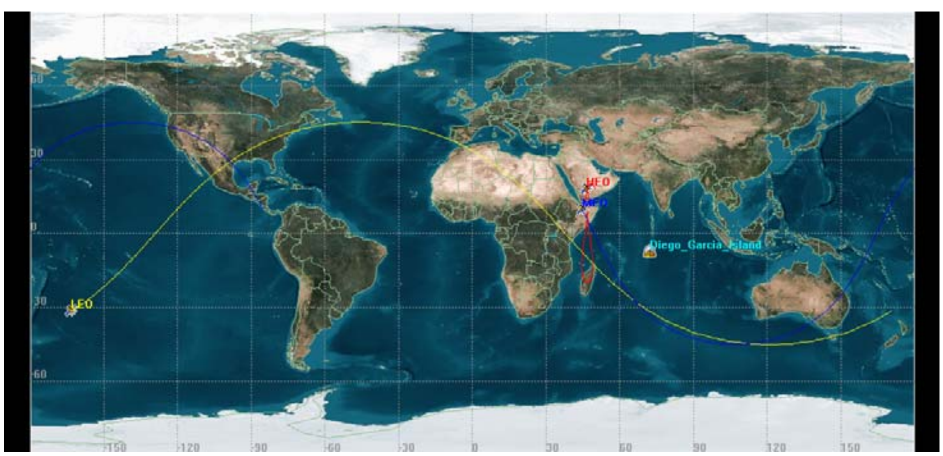

Figure 9 - Diego Garcia Tracking Station STK Scenario

AFSCN Link Predictor

The AFSCN LP models the C/No over a support vs. time for uplink. For downlink, it models the BER performance over time. The two functional signatures for the downlink and uplink performance are:

Compute_DL_BER_Perf(*SC_Power, DR, MI, f, Link_Geom, Time_step*);

Compute_UL_PtNo(*Ta, NF, ES_Power, SC_Insertion_Loss, f, Link_Geom, Time_step*);

These functions require multiple input parameters from the user, defined in Table 3.

Table 3 - AFSCN LP Inputs

Input	Definition
SC_Power	Spacecraft power
DR	Data rate of the subcarrier
MI	Modulation index
f	frequency
Link_Geom	Time-based array of elevation angle, range, and degrees off-boresight vs. time
Time_step	Time step between data points of geometric array
Ta	Noise temperature received from the earth
NF	Noise figure of spacecraft. Topex Omni antenna model used
ES_Power	Earth station power

The downlink function will output time-based BER plots while the uplink function only provides time-based SNR plots.

AFSCN LP design

The system design of the AFSCN LP will be explained using IDEF0, integrated definition for functional modeling. The components of this tool will be described with an integrated dictionary and two normative use cases will illustrate how this tool may be used.

AFSCN LP architecture

The SV-4 System Functional Description, is used to illustrate the design of this software. The primary function of this software is to predict uplink and downlink performance. The context diagram of the AFSCN LP is in Figure 10 and the diagram in Figure 11 illustrates the various Inputs, Controls, Outputs, and Mechanisms (ICOMs) required by the tool. Also, the ICOMs are explained in detail captured by an integrated dictionary. The lower level functional diagrams are located in Appendix A.

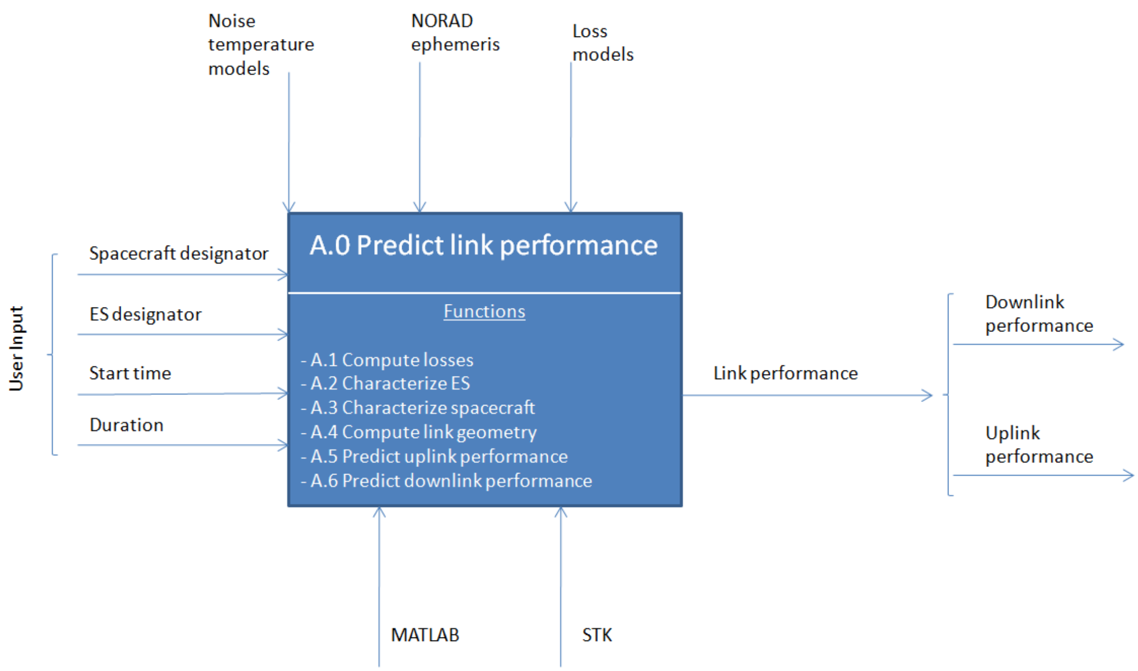

Figure 10 - A-0 AFSCN LP Context Diagram

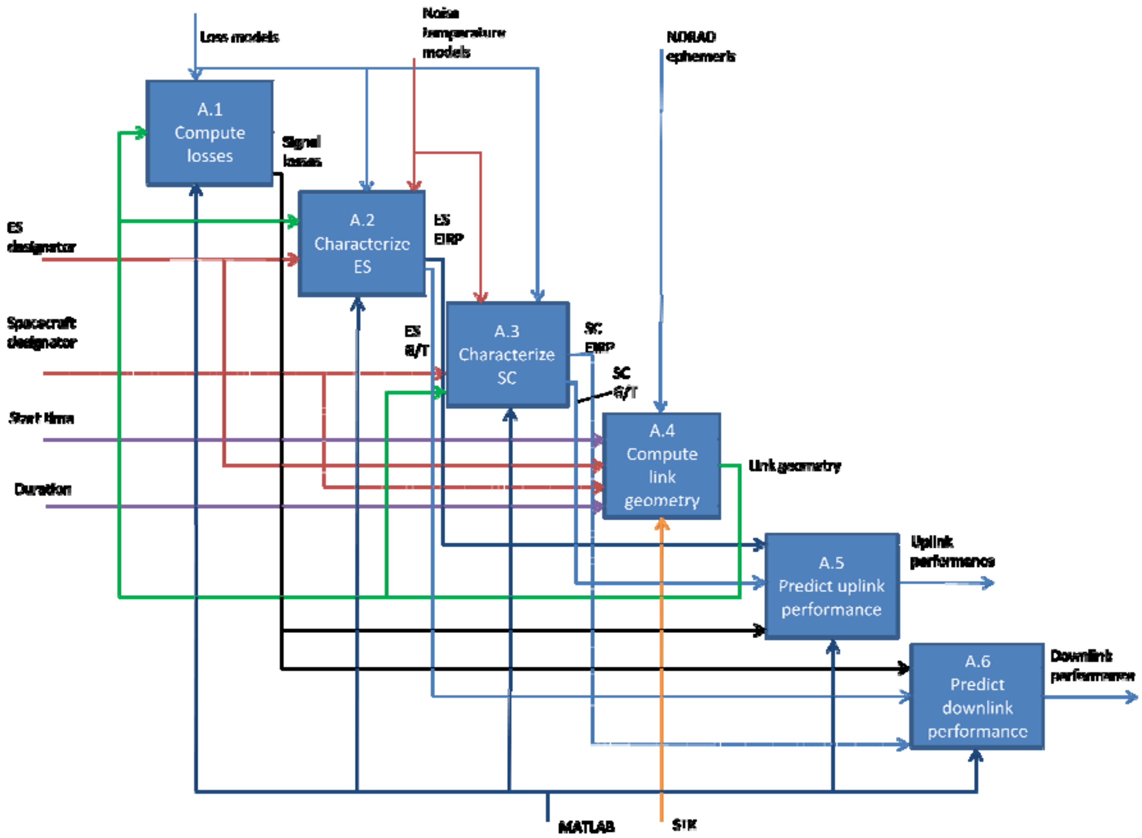

Figure 11 - A0 Activity Diagram

Integrated dictionary

User input

- Description: The user is the actor who will use the system. The user will input the relevant data for the link; Start time, Duration, Spacecraft designator, and Earth station designator.
- Relationships: Input to A.0(Predict link performance)

Note: Using STK, the start time and duration are chosen. However, using the AFSCN LP function in MATLAB, there is no “Spacecraft Designator” or “Earth station designator” input into the function. These titles are meant to be representative of the various user inputs. In practice, the user would be able to select the RTS and spacecraft configuration from a drop down menu with the necessary parameters from those selections saved in a database.

Spacecraft designator

- Description: User input. The spacecraft designator input includes all information needed from the spacecraft for performance calculations. The spacecraft designator is part of the information needed to determine the link geometry.
- Relationships: Input to A.4 (Compute link geometry) and A.3 (Characterize SC)

Link Geometry

- Description: STK takes the spacecraft designator, Earth station (ES) designator, start time, and duration as inputs and generates geometry for the link. The values include degrees off-boresight, range, and elevation. The geometry values are used in various link calculations.
- Relationships: Output from A.4 (Compute link geometry). Input to A.1 (Compute losses), A.2(Characterize ES), and A.3(Characterize SC).

ES designator

- Description: User input. The ES designator identifies the earth station used in the link. The earth station location is part of the information needed in determining the link geometry.
- Relationships: Input to A.2(Characterize ES) and A.4(Compute link geometry)

Start time

- Description: User input. The start time will be used by STK as part of the information needed to generate the arrays.
- Relationships: Input to A.4(Compute link geometry)

Duration

- Description: User input. STK will determine the link geometry for the duration specified and generate geometric arrays for the given link if the link is available for that start time and duration. This value is in seconds
- Relationships: Input to A.4(Compute link geometry)

Noise temperature models

- Description: These are the models used in determining the system noise temperature of the spacecraft and the earth station.
- Relationships: Control to A.2(Characterize ES) and A.3(Characterize SC)

Note: These temperature models can be updated if more accurate models become available. Also, additional noise models may be included for increased fidelity of performance estimates.

NORAD ephemeris

- Description: STK utilizes ephemeris information from NORAD. The ephemeris is updated periodically.
- Relationships: Control to A.4(Compute link geometry)

Loss models

- Description: The loss models are used to predict the signal losses inherent in each link.
- Relationships: Control to A.1(Compute losses)

Note: These loss models can be updated if more accurate models become available. Also, additional loss models may be included for increased fidelity of performance estimates.

MATLAB

- Description: This is the software used to develop all of the functionality of this system, not including the link geometry determination.
- Relationships: Mechanism to A.1(Compute losses), A.2(Characterize ES), A.3(Characterize SC), A.5(Predict uplink performance), and A.6(Predict downlink performance)

STK

- Description: STK was used to determine link access and to generate the array of orbital location for the desired link.
- Relationships: Mechanism to A.4(Compute link geometry)

Signal Losses

- Description: The signal losses are predicted using various loss models.

- Relationships: Output from A.1(Compute losses). Input to A.5(Predict uplink performance) and A.6(Predict Downlink performance)

ES EIRP

- Description: The EIRP is a value needed to determine the uplink performance. Calculated using the SC parameters and input from the user.
- Relationships: Output to A.2(Characterize ES). Input to A.5(Predict uplink performance).

ES G/T

- Description: ES gain over temperature. Calculated using ES parameters, temperature models, and elevation data.
- Relationships: Output from A.2(Characterize ES). Input to A.6(Predict downlink performance)

SC EIRP

- Description: Spacecraft EIRP. Calculated using the SC parameters and input from the user.
- Relationships: Output from A.3(Characterize SC). Input to A.6(Predict downlink performance).

SC G/T

- Description: Spacecraft gain over temperature. Calculated using SC parameters, temperature models, and DOFF.
- Relationships: Output from A.3(Characterize SC). Input to A.5(Predict uplink performance).

Downlink performance

- Description: This is the predicted performance of the downlink. This will be in the form of time based plots.
- Relationships: Output from A.6(Predict link performance)

Uplink performance

- Description: This is the predicted performance of the uplink. This will be in the form of time based plots.
- Relationships: Output from A.5(Predict uplink performance)

Future AFSCN architecture

The AFSCN LP was designed from the bottom-up meaning its place in the architecture of the AFSCN was not previously determined before creating the AFSCN LP. The functionality of performance prediction was established and then adopted for use within the AFSCN. The current design of the AFSCN LP requires spacecraft ephemeris (i.e., location) updates from NORAD because that is what STK requires. During a contact, a user's spacecraft location information is updated with current tracking information obtained during the contact from the RTS. The users use this tracking data to update the known location of their spacecraft. This, of course, differs from the way STK and, in turn, the AFSCN LP obtains spacecraft ephemeris information. One of the requirements needed to ensure that this tool is useful, is timely and precise orbit information. This is an issue because it is not known whether or not the ephemeris updates received from NORAD by STK would meet the accuracy and timeliness requirements needed by the users in order to utilize the AFSCN LP. To solve this issue, the users would need a way to bypass the need for NORAD ephemeris updates to STK and enter their own ephemeris updates based on tracking information received from the AFSCN. This is one hurdle in implementing this tool into the AFSCN. Assuming this issue is solved, a possible implementation of the AFSCN LP into the AFSCN will now be discussed.

The AFSCN LP software would be loaded onto a CPU at a workstation located in the orbital analyst section of the SOC/External users' facility. The spacecraft ephemeris information would then be loaded into the AFSCN LP in preferably an automated fashion. Currently, the AFSCN LP is designed to only predict the performance of RBC system links on the AFSCN. However, if this was implemented it would need to be able to predict link performance on all of the varied RTS's in the AFSCN. There are multiple RTS configurations on the AFSCN and the AFSCN LP would need to be updated to allow the user to determine which RTS would be best suited for their needs. Some RTS's are more capable than others and would provide a better SNR. Also, hardware and software updates to the RTSs may result in increased/decreased performance.

On the spacecraft side of the link, the AFSCN LP makes certain assumptions about the spacecraft such as; the antenna type, transmission power, signal loss models, etc. However, in practice those assumption are not always valid and all spacecraft configurations must be accounted. Continuous updates will be needed to that take into account new spacecraft launches and changes in performance of existing spacecraft. Considering the updates required on the RTS and spacecraft sides of the link, there needs to be a mechanism to update the tool to adjust for these changes. These updates could be released as a software patch periodically. The proposed architecture that takes into account the previous considerations and assumptions is illustrated below in the OV-2 diagram in Figure 12.

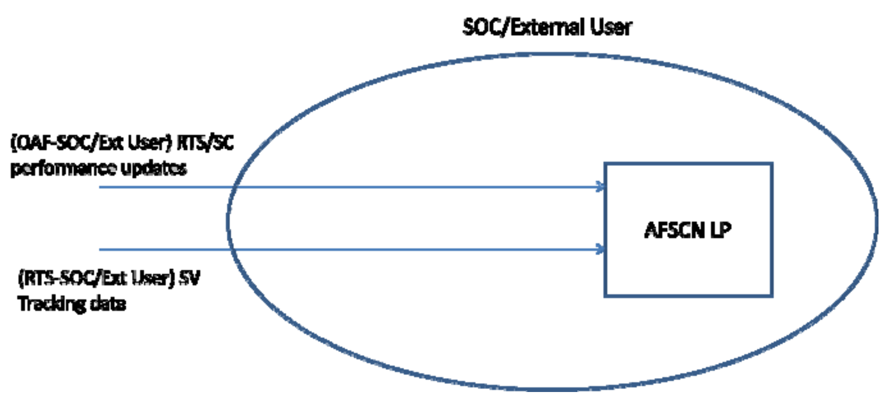

Figure 12 - AFSCN LP OV-2

The (OAF-SOC/ExtUser) needline would need to include additional information. “RTS/SC performance updates” would be the vehicle for the needed updates to the AFSCN LP that encompass updates to AFSCN-wide spacecraft and RTS performance parameters. The OAF would compile the updates through their own process and disseminate it to the users. The ephemeris updates to the AFSCN LP would be provided by the existing “SV Tracking data” information exchange encompassed in the (RTS-SOC/ExtUser) needline. Table 4 further describes the additional information exchange required within the (OAF-SOC/ExtUser) needlines and the current information exchange from the RTS required by the AFSCN LP.

Table 4 - AFSCN LP OV-3 Matrix

Need Line	Information Exchange	Source Activity	Destination Activity	Content
OAF-SOC/ExtUser	AFSCN LP Update	Disseminate spacecraft and RTS performance updates	Receive and install AFSCN LP software update	Spacecraft and RTS performance parameters
RTS-SOC/ExtUser	SV Tracking data	Send Tracking Data to SOC	Receive tracking data	Antenna azimuth angle, antenna elevation angle, slant range, calculated range rate, time tag, mode

Now the method of disseminating these updates needs to be explored. The AFSCN currently utilizes a closed network. The communications segment of the AFSCN is self contained and is not connected to any other network. Any updates to the operational software of the RTS’s must be accomplished in one of two ways. A CD-ROM can be shipped to each RTS and then installed on the system. Or the software update can be uploaded to an online database connected to the world wide web and then accessed via a web enabled terminal at the RTS. The software can then be downloaded to a CD-ROM and installed on the system. This method could be utilized by the users to update the AFSCN LP.

This AFSCN LP architecture is intentionally simple because the AFSCN is already a complex system-of-systems (SoS); any added complexity would not be welcomed. This approach would allow the least amount of disruption and added complexity to the AFSCN possible. The users would be encouraged, not required, to utilize the AFSCN LP.

IV. Analysis and Results

Chapter overview

The AFSCN LP was created to demonstrate the utility of performance prediction and its potential use in the AFSCN. Here simulations are run assuming representative spacecraft configurations and orbits. The AFSCN LP software is currently only written to predict the performance of AFSCN links that utilize RBC RTS's. The simulations model the performance of SGLS links assuming the spacecraft is utilizing an Omni antenna at representative LEO, MEO, and HEO orbits. The link performance is modeled at two separate AFSCN RTS's located at Diego Garcia, British Indian Ocean Territory (BIOT) and Colorado Springs, CO. Only the simulations ran at Diego Garcia will be analyzed because the goal of the analysis can be expressed with only one location. Also, performance was modeled for up and downlink but only the downlink performance will be analyzed because it has more use to AFSCN applications because the amount of data passed during uplink is relatively small given the capability of the earth station and the spacecraft. Therefore, predicting uplink SNR may not be a useful application of this tool.

DGS downlink performance simulation

Table 5 is from the AFSCN SIS 502, which shows the various subcarrier parameters and capabilities of the SGLS waveform.

Table 5 - RBC SGLS Telemetry Subcarrier (AFSCN, 2004)

S/C Frequency	S/C Modulation	PCM Codes	Data Rate	Carrier Mod Index
1.024 MHz	BPSK (1.57 rad ± 10%)	NRZ-L, M, S Biϕ-L, M, S	100 bps to 128 kbps	0.3 to 1.85 radians
1.25 MHz	BPSK (1.57 rad ± 10%)	NRZ-L, M, S Biϕ-L, M, S	1 kbps to 32 kbps	0.2 to 1.45 radians
1.7 MHz	BPSK (1.57 rad ± 10%)	NRZ-L, M, S Biϕ-L, M, S	100 bps to 256 kbps	0.3 to 1.85 radians

The data rate is limited by the spectral proximity of the subcarriers (AFSCN, 2004). The 1.7 MHz subcarrier will be modeled in the following simulations with the maximum data rate assumed and the modulation index held constant. The carrier frequency, f, will be set at a representative value. The spacecraft power will be varied to illustrate the utility of the AFSCN LP. Table 6 provides values used in the simulations.

Table 6 - AFSCN LP Simulation Parameters

Input	Value
SC_Power	dBm, Varied
DR	256 kbps
MI	0.7
f	2247.5 MHz
Link_Geom	Dependent on the link
Time_step	LEO = 10s, MEO,HEO = 1 min

Results

Figures 13, 14, and 15 are plots of BER vs. Time for a LEO, MEO, and HEO orbit, respectively. Again, these links were modeled at Diego Garcia Tracking Station (DGS) and the input parameters are listed in Table 4. In all of the plots, the BER follows a similar pattern. The dominant 'V' shape of the plot is due the system noise temperature model assumed in the AFSCN LP. The midpoint of each plot corresponds to the largest elevation angle and resulting in the smallest noise power contribution from the earth and that yields a higher SNR and in turn a smaller BER. The other contributions to the performance were explained previously in the Methodology Chapter. In the BER plots below, time starts at zero and ends when the support is over. However, if this were implemented in the AFSCN the boundaries of the plots would be held at the start and stop times of the determined availability of the support.

In each set of plots, the left plot is modeled with a lower spacecraft power than the plot on the right. As expected, increasing the spacecraft power decreases the BER over the support. Users require a maximum BER over a support to obtain the desired resolution. Typically, users require a maximum BER of $1x10^{-5}$ for a support to be considered successful. To demonstrate the potential use of this tool, the spacecraft power was set at the value needed to obtain a BER of approximately10^{-5}. With a maximum BER value needed, it is clear from the Figures below that portions of the supports would not be useful to the users because the maximum BER requirement is not met.

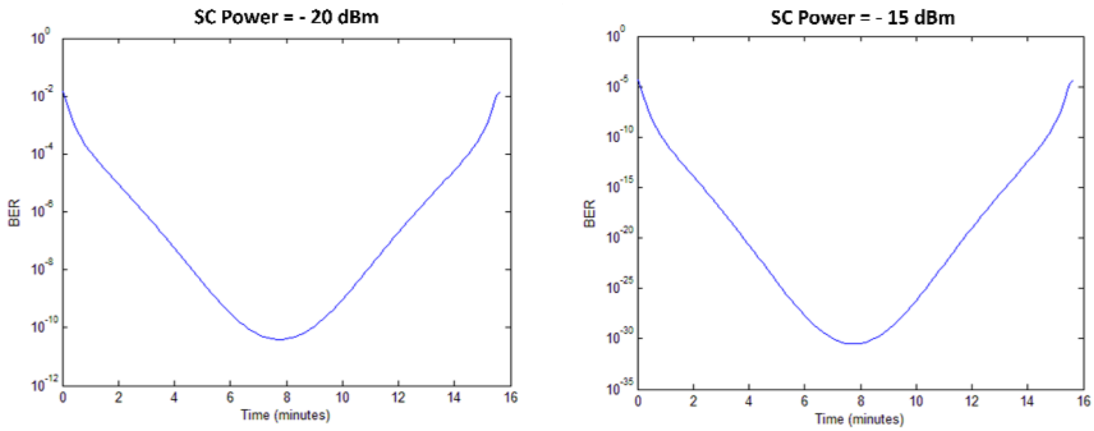

Figure 13 - DGS LEO BER Performance

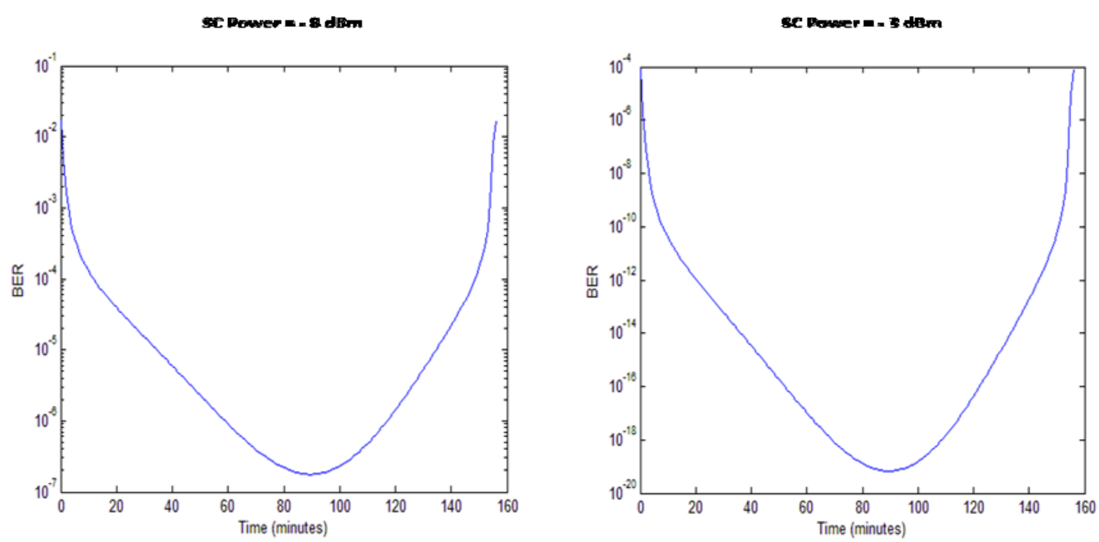

Figure 14 - DGS MEO BER Performance

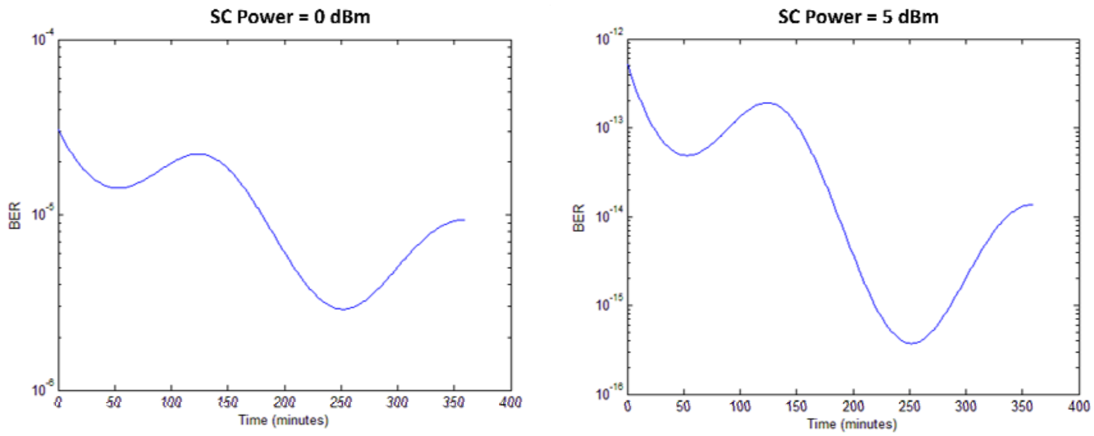

Figure 15 - DGS HEO BER Performance

AFSCN Applicability

These results demonstrate two potential uses for performance prediction (i.e., the AFSCN LP) within the AFSCN. By knowing the predicted BER over a support the user can request support only when the desired BER will be obtained, freeing up time for other supports on the AFSCN. Also, spacecraft operating organizations can adjust the spacecraft power to obtain the desired BER, saving the spacecraft precious energy.

The users will have the capability to schedule support on the AFSCN more efficiently. With the performance throughout a future support known the user can schedule their time on the AFSCN during the time interval the desired BER is possible, not before or after. The left plot in Figure 13 helps to illustrate this point. The user enters a desired start time, end time, spacecraft configuration, and ground station. This request is for the user's LEO spacecraft, with data pulled down from Diego Garcia. Also, its assumed the user has a maximum BER requirement of 10^{-7} and that the selected spacecraft configuration sets the spacecraft power to -20dBm. With all of the necessary information entered, the user gets a BER plot. This is the left plot in Figure 13. From the plot, it is clear that the user will not receive the desire performance for a portion of the selected time interval. In fact, approximately 8 minutes of 16 minute support does not yield the desired BER and would be useless to the user and the AFSCN. With this knowledge, the user can request a smaller support window, freeing up time for other potential supports. The same conclusions can be made from the representative MEO and HEO downlinks in Figures 14 and 15, respectively.

The AFSCN LP not only demonstrates how time on the AFSCN may be saved, it also demonstrates how it might be used to save spacecraft power. As stated previously, the BER plots were generated by adjusting the spacecraft power to only what was needed to obtain a BER of approximately 10^{-5}. This approach could also be used by the users to save power on their respective spacecrafts. In the right side plots of Figures 13, 14, and 15, it is clear that the BER performance is well over what is typically needed by most users. That power could be saved by understanding the predicted performance of a future support and lowering the spacecraft power to only what is required to obtain the desired BER.

V. Conclusions and Recommendations

Research conclusions

How can link performance be predicted?

The AFSCN LP was created to answer this question. The physics and models behind this tool were explained and similar tools were studied to determine potential applicability to the AFSCN LP. Models from one of those tools, The Telecom Forecaster, were used within the AFSCN LP. This AFSCN LP was created to illustrate the utility of link performance prediction in the AFSCN and not to be a final product. The AFSCN LP would need to be integrated into a more user friendly interface and include all spacecraft and ground station configuration to be of use to a user of the AFSCN.

Where in the current AFSCN architecture would performance prediction be applied?

The current architecture of the AFSCN was studied to determine what prediction capability, if any, exists in the AFSCN. It was found that only RFI interference prediction was conducted and nothing related to SNR or BER performance prediction is used. These conclusions were drawn from architecture diagrams of the AFSCN. To gain more insight into AFSCN/user operations a couple SOCs were contacted, but due to security reasons the current processes were not revealed.

The AFSCN LP was designed and built from the bottom-up. After, the software behind the tool was complete the ICOMs were understood. With required ICOMs of the tool understood, its potential place in the AFSCN was identified. It was decided that the best place for the AFSCN LP was within the SOCs at a separate workstation with the AFSCN LP software loaded onto a standalone CPU as illustrated is a previous OV-2.

This again is to keep the disruption of current AFSCN operations down to a minimum. A problem was identified. The tool requires accurate spacecraft location information and for that continuous ephemeris updates are needed. Currently, STK utilizes ephemeris updates from NORAD but it is not known if that would meet the accuracy/timeliness requirements needed for the AFSCN LP to be useful. This would be an area for future study. Also, this tool would require software updates. An existing process by which operational RTS software obtains updates was used.

How would the AFSCN and various users benefit from having link prediction capability?

With this capability, the users would be given the option to use this tool with the goal of more efficiently scheduling time on the AFSCN and allowing the user to potentially adjust spacecraft power to optimal levels. These benefits were illustrated by running simulations on the AFSCN LP. Downlink simulations were run with the ground station at Diego Garcia and representative spacecraft at LEO, MEO, and HEO orbits. The simulation yielded BER plots vs. time. These plots showed what the user might see if this tool was used in the AFSCN and it was explained how the information in these plots might be used to save time on the network and power on spacecraft.

Significance of research

The research conducted is significant because time across the AFSCN is limited and a performance prediction capability could allow the more effective, and efficient, scheduling of more supports. Also, if this tool were to prove useful in saving power on spacecraft and was a robust part of the AFSCN architecture, users would be able to use the extra power to better meet their mission needs, or extend mission endurance.

Furthermore, during spacecraft design the worst case link budget would not have to be assumed with this new capability. The designers could relax that requirement, which could potentially save weight (i.e., cost) on the spacecraft.

It should also be noted that the AFSCN LP was a proof-of-concept. Given more time and resources this tool could easily be brought up to operational status.. The real challenge is operationally integrating this capability within and across the legacy systems of the AFSCN system-of-systems. This paper serves as a first step toward implementing performance prediction capability into the AFSCN.

Recommendation for future research

The applicability of this tool was focused on time savings on the AFSCN and power savings on user spacecraft. To fully understand the potential utility of this capability, the operational processes of AFSCN and its users must be better understood. Issues with classification levels did not allow this research to fully detail those operational processes. Research at a higher classification level would be necessary to fully demonstrate the utility of performance prediction; the benefits are real but a quantitative analysis of these benefits would be crucial.

Recommendation for future implementation

Many things would need to happen for the AFSCN LP to be ready for implementation into the AFSCN. Currently, it only models the RBC ground stations at two separate locations. It would need to model all ground station configurations at all locations- Diego Garcia and Colorado Springs. Also, only one basic spacecraft configuration is modeled at different orbits. In order for this tool to be useful it would need to model all spacecraft configurations. Further research and testing on these physics-based models would need to be carried out in order to ensure the highest level of accuracy. Basically, this capability would need to go through an entire systems engineering process before implementation. Also, the AFSCN LP only predicts the performance of one telemetry subcarrier. In practice this tool would need to predict the performance of multiple subcarriers.

To determine the BER of the links, a theoretical model was used where given an Eb/No, the BER could be determined. This assumes theoretical performance of the ground station equipment. To increase the accuracy of the AFSCN LP, the actual BER performance of the ground station equipment would need to be determined. This performance would be particular to each ground station even of the same configuration (e.g., RBC). The actual site performance would need to be updated periodically into the software of the AFSCN LP to take into account hardware and software updates of the ground station.

Conclusion

The AFSCN and its users could greatly benefit from having the capability to predict link performance. The AFSCN LP was created to help demonstrate the utility of such a capability. It was shown that by predicting the BER over an AFSCN support, the user would have the option to schedule less time on the Network or adjust the spacecraft's power level to the optimal setting, saving power. It was also explained where prediction capability might fit into the current architecture of the AFSCN. The proposed architecture would impart minimal impact on current AFSCN operations while, allowing for increased efficiency, in time on the Network and power on spacecraft.

Appendix A – AFSCN LP activity models

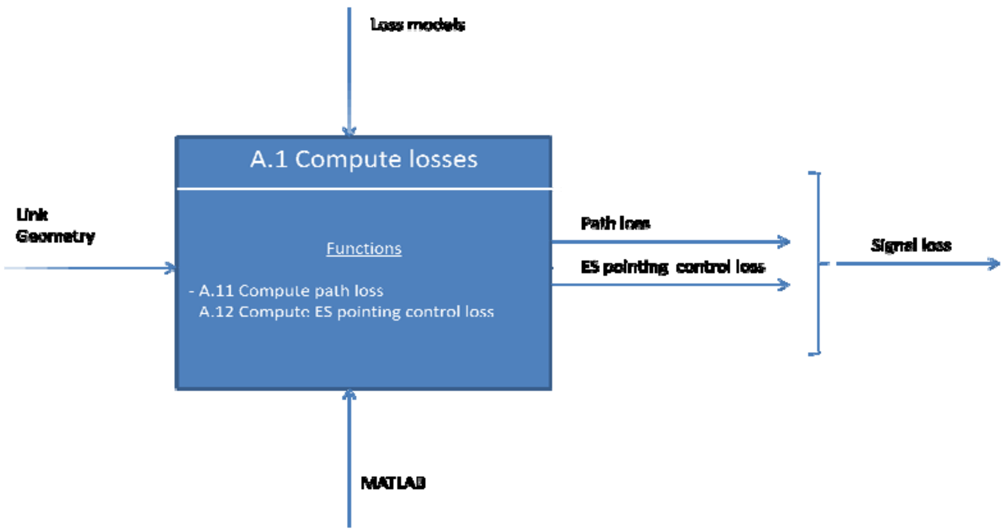

Figure 16 - A.1 Compute Losses

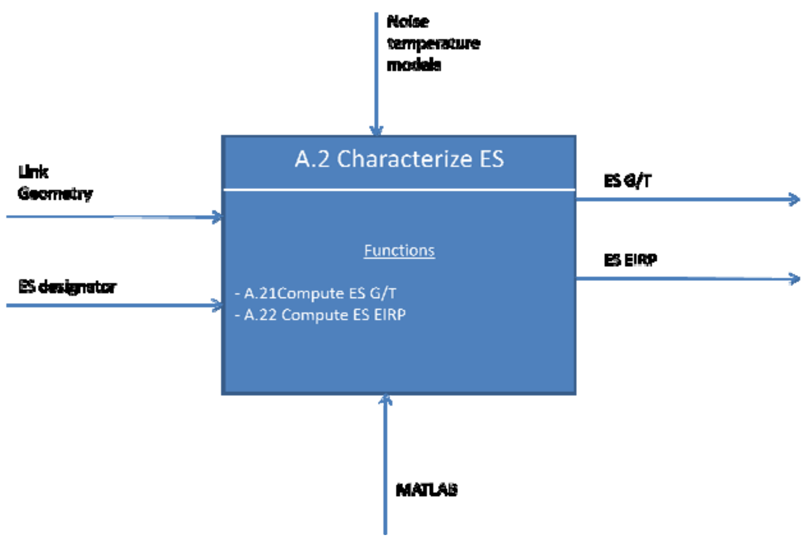

Figure 17 - A.2 Characterize Earth Station

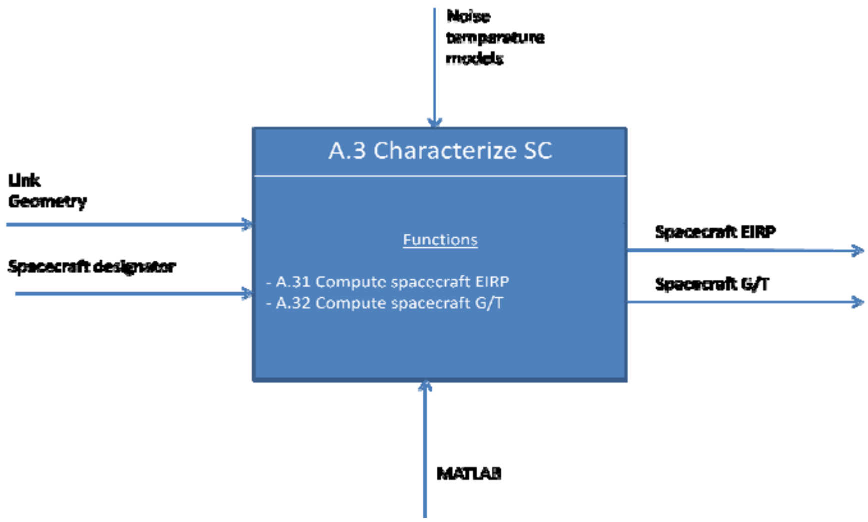

Figure 18 - A.3 Characterize Spacecraft

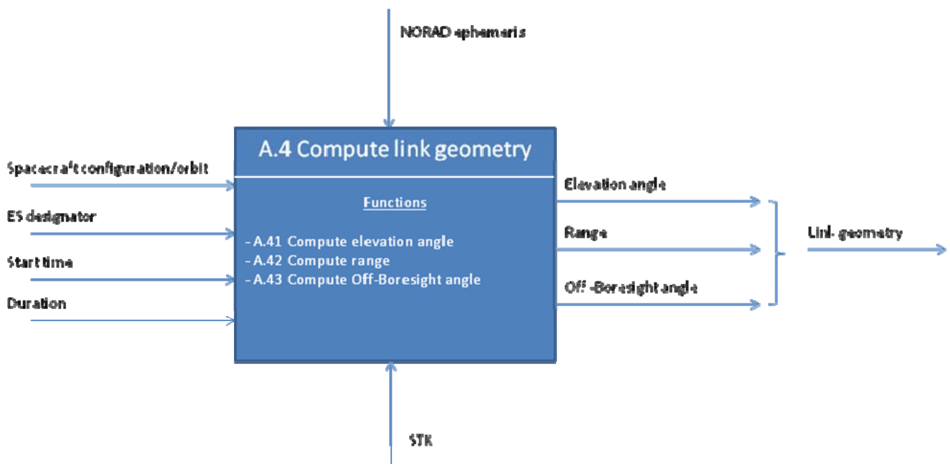

Figure 19 - A.4 Compute Link Geometry

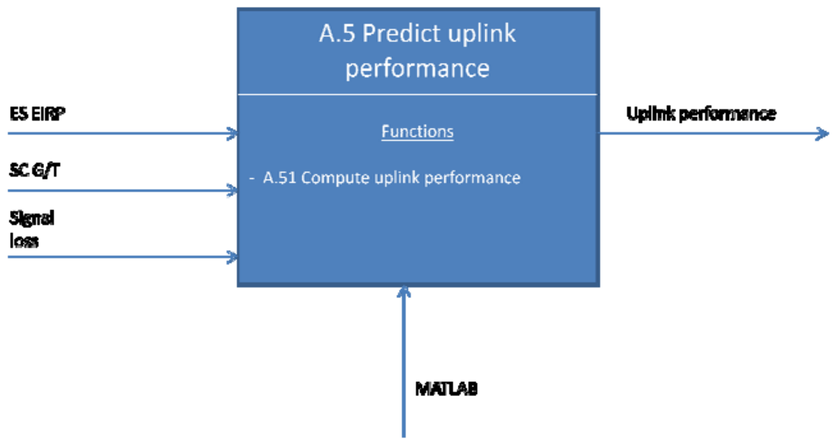

Figure 20 - A.5 Predict Uplink Performance

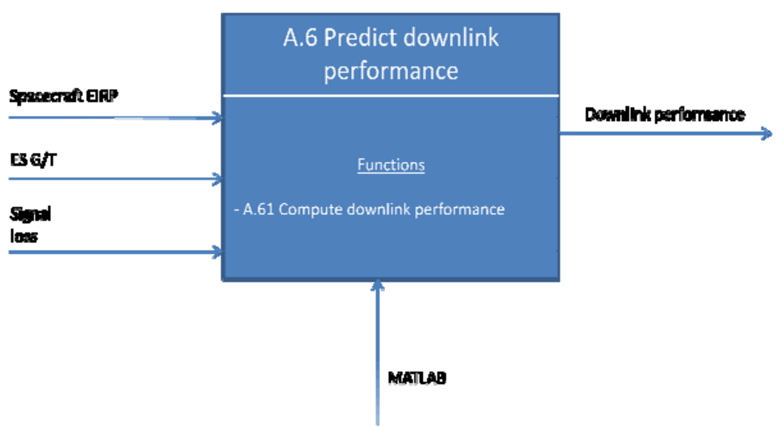

Figure 21 - A.6 Predict Downlink Performance

Appendix B – Performance prediction simulations

Scenario 1 (Uplink)

Compute_UL_PtNo(Ta, NF, ES_Power, SC_Insertion_Loss, f, Link_Geom, Time_step);

CTS

Ta = 290 (Over land) for all CTS uplink scenarios
NF = 1.76 (from Topex Omni model), for all CTS uplink scenarios
ES Power = 60 dBm, for all CTS uplink scenarios
f = 14GHz, for all CTS uplink scenarios
Link_Geom = CTS_LEO, CTS_MEO, or CTS_HEO
CTS_LEO, Time_step = 10s
CTS_MEO, Time_step = 60s
CTS_HEO, Time_step = 60s

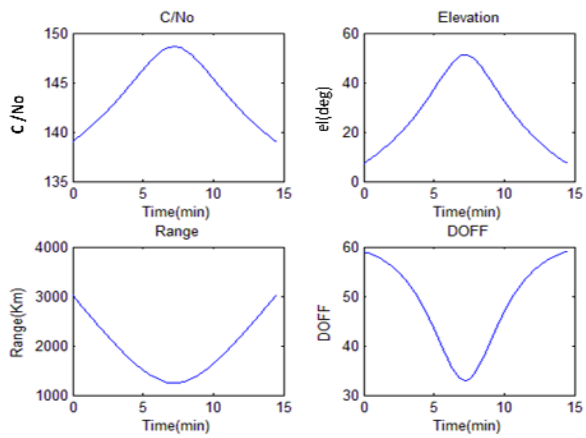

Figure 22 - CTS LEO Uplink Performance

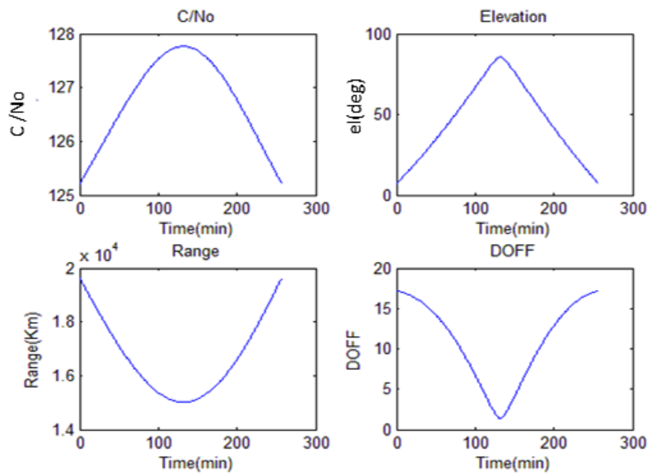

Figure 23 - CTS MEO Uplink Performance

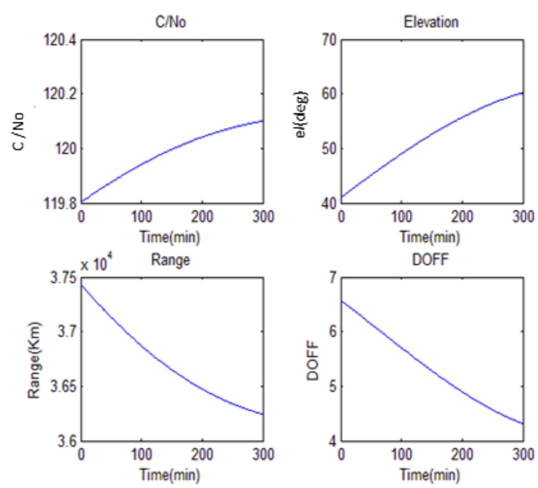

Figure 24 - CTS HEO Uplink Performance

DGS
Ta = 150 (Over ocean) for all DGS uplink scenarios
NF = 1.76 (from Topex Omni model), for all DGS uplink scenarios
ES Power = 60 dBm, for all DGS uplink scenarios
f = 14GHz, for all DGS uplink scenarios
Link_Geom = CTS_LEO, CTS_MEO, or CTS_HEO
CTS_LEO, Time_step = 10s
CTS_MEO, Time_step = 60s
CTS_HEO, Time_step = 60s

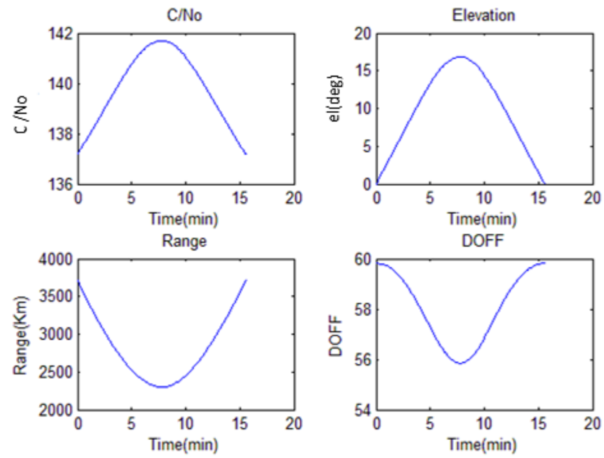

Figure 25 - DGS LEO Uplink Performance

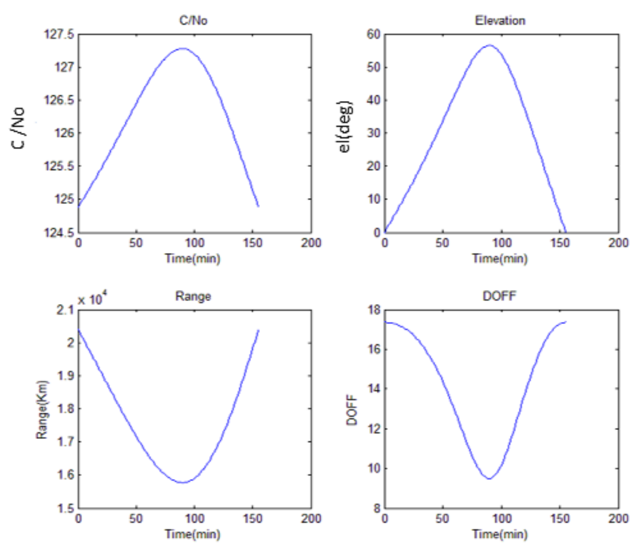

Figure 26 - DGS MEO Uplink Performance

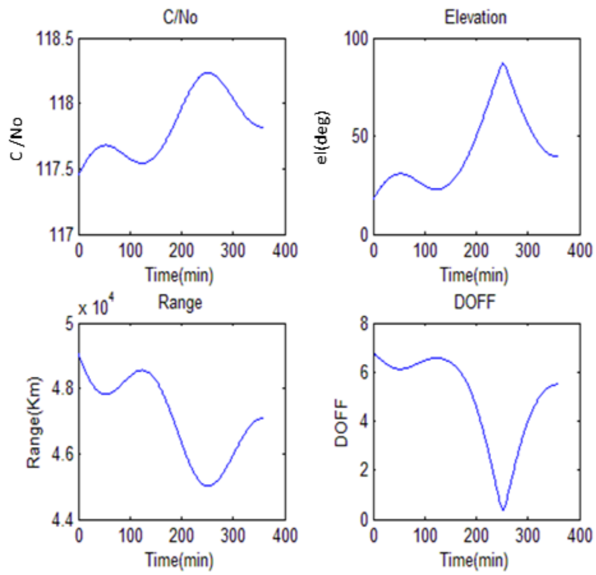

Figure 27 - DGS HEO Uplink Performance

Scenario 2 (Downlink)

Compute_DL_PtNo(SC_Power, f, Link_Geom, Time_step);

CTS
For all CTS downlinks, SC power = 5dBm, f = 12GHz
Link_Geom = CTS_LEO, CTS_MEO, or CTS_HEO
CTS_MEO, Time_step = 60s
CTS_HEO, Time_step = 60s

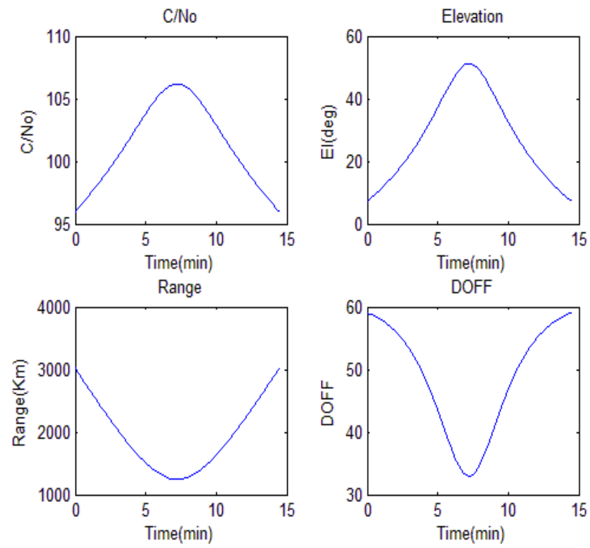

Figure 28 - CTS LEO Downlink Performance

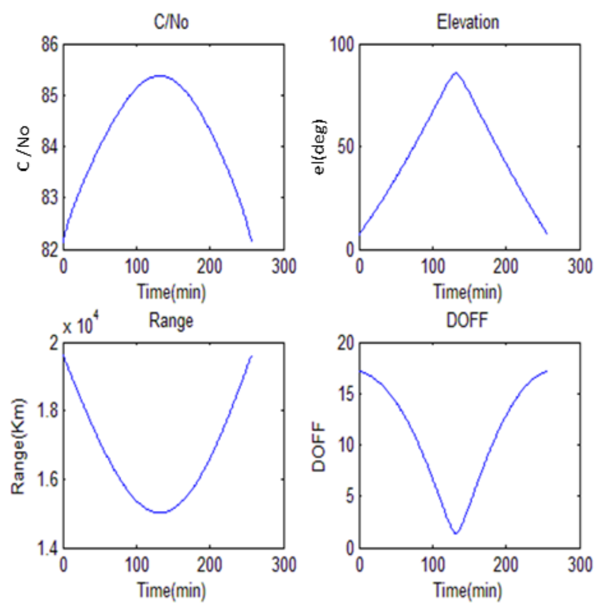

Figure 29 - CTS MEO Downlink Performance

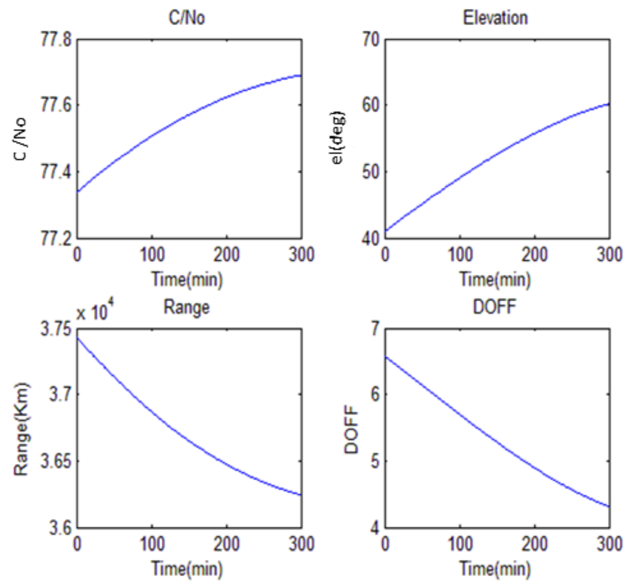

Figure 30 - CTS HEO Downlink Performance

DGS

For all DGS downlinks, SC power = 5dBm, f = 12GHz
Link_Geom = DGS _LEO, DGS _MEO, or DGS_HEO
DGS _MEO, Time_step = 60s
DGS _HEO, Time_step = 60s

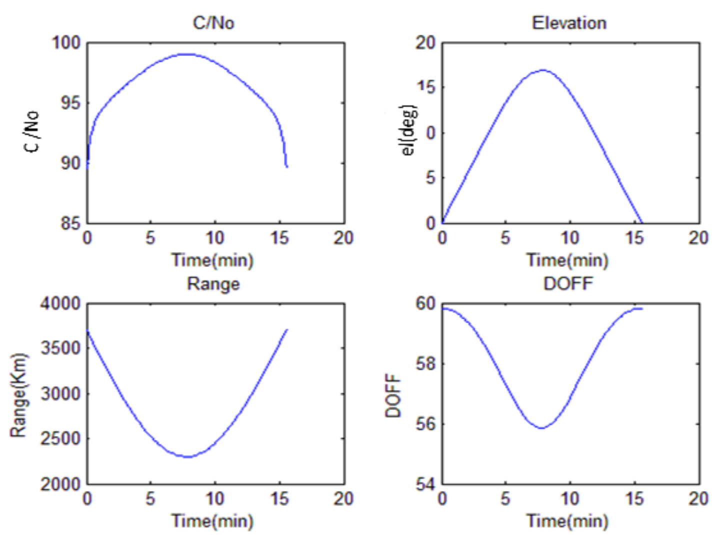

Figure 31 - DGS LEO Downlink Performance

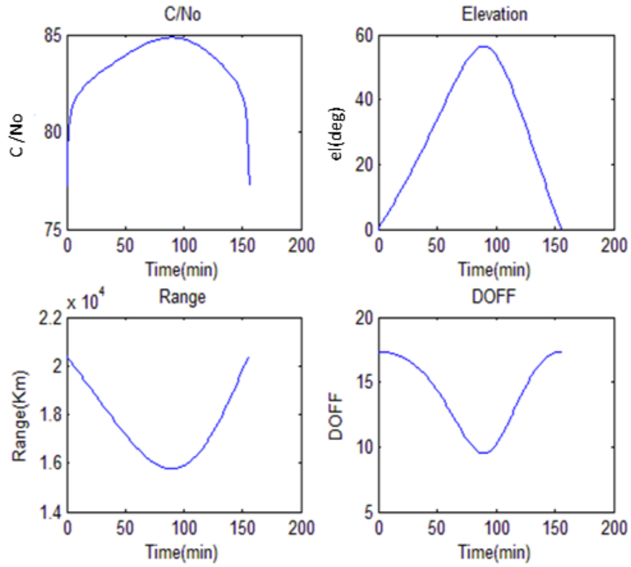

Figure 32 - DGS MEO Downlink Performance

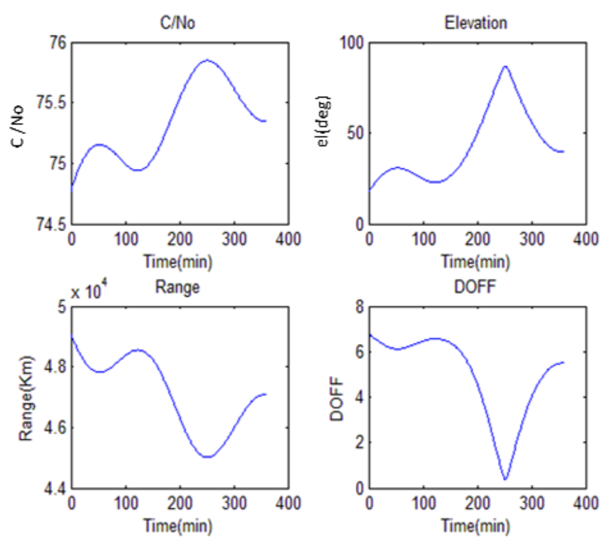

Figure 33 - DGS HEO Downlink Performance

Appendix C – MATLAB functions

Compute_DL_BER_Perf

```
function [ DL_BER_perf ] = Compute_DL_BER_Perf(SC_Power, DR, MI, f,
Link_Geom, Time_step);


el = Link_Geom(:,1);
Range = Link_Geom(:,2);
DOFF = Link_Geom(:,3);

ES_Gain = Compute_ES_Gain(f);

Path_Loss = Compute_Path_Loss(f, Range);

ES_Ts = Compute_ES_Ts(el);

DL_PtNo = Compute_DL_PtNo(SC_Power, f, Link_Geom, Time_step);

SC_EIRP = Compute_SC_EIRP(SC_Power, DOFF);

Signal_Power_at_LNA = SC_EIRP + ES_Gain + Path_Loss;

a = size(Link_Geom);

Array_size = a(1,1);

Total_time = Array_size*Time_step;

Time = [0:Time_step:Total_time - Time_step];% Time in seconds
corresponding to a 1 minute time step from STK data

TLM_EbNo = Compute_TLM_EbNo(DL_PtNo, MI, DR);


DL_BER_perf = .5*erfc(sqrt(10.^(TLM_EbNo./10))); % Theoretical BER
function

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%

% subplot(1,1,1); plot( Time,DL_BER_perf,...
%   'DisplayName','Time vs. BER Performance');

semilogy(Time,DL_BER_perf);

title({'BER Performance'});
ylabel({'BER'});
xlabel({'Time (minutes)'});


% subplot(3,3,1); plot( Time,DL_BER_perf,...
%   'DisplayName','Time vs. BER Performance');
%
```

```
% semilogy(Time,DL_BER_perf,'Parent',subplot(3,3,1),'DisplayName','Time
vs. BER Performance');
%
%
% title({'BER Performance'});
% ylabel({'BER'});
% xlabel({'Time (minutes)'});
%
% subplot(3,3,2); plot(Time,Signal_Power_at_LNA,...
%     'DisplayName','Time vs. Signal Power at LNA ');
%
% title({'Signal Power at LNA'});
% ylabel({'Signal Power'});
% xlabel({'Time (minutes)'});
%
%
%
% subplot(3,3,3); plot(Time,TLM_EbNo,...
%     'DisplayName','Time vs. Telemetry Eb/No ');
%
% title({'Telemetry Eb/No'});
% ylabel({'Eb/No'});
% xlabel({'Time (minutes)'});
%
%
% subplot(3,3,4); plot( Time, el,...
%   'DisplayName','Time vs. Elevation');
%
% title({'Time vs. Elevation'});
% ylabel({'Elevation'});
% xlabel({'Time'});
%
% subplot(3,3,5);plot(Time,DL_PtNo,...
%     'DisplayName','Time vs, C/No');
%
% title({'C/No'});
% ylabel({'C/No'});
% xlabel({'Time (minutes)'});
%
% subplot(3,3,6); plot(Time,ES_Ts,...
%     'DisplayName','Time vs. Ts');
%
% title({'Ts'});
% ylabel({'Ts (K)'});
% xlabel({'Time (minutes)'});
%
% subplot(3,3,7); plot(Time,DOFF,...
%     'DisplayName','Time vs. DOFF');
%
% title({'Degrees off Boresight'});
% ylabel({'DOFF'});
% xlabel({'Time (minutes)'});
%
% subplot(3,3,8); plot(Time, Range,...
%     'DisplayName','Time vs. Range');
```

```
%
% title({'Range'});
% ylabel({'Range'});
% xlabel({'Time (minutes)'});

end
```

Compute Telemetry Eb/No

```
function [ TLM_EbNo ] = Compute_TLM_EbNo( DL_PtNo, MI, DR);

Svs_Mod_Loss = Compute_Svs_Mod_Loss(MI);

TLM_EbNo = DL_PtNo + Svs_Mod_Loss - 10*log10(DR);

end
```

Compute Downlink Pt/No

```
function [ DL_PtNo ] = Compute_DL_PtNo(SC_Power, f, Link_Geom,
Time_step);

% Computes the downlink carrier power to noise density and produces
% corresponding plots

el = Link_Geom(:,1);     % extracts elevation from the geometry array
Range = Link_Geom(:,2);  % extracts range from the geometry array
DOFF = Link_Geom(:,3);   % extracts DOFF from the geometry array

Range_in_Km = Range/1000;

k = ((1.3806504*10^-23)); % Boltzmann's constant

dBk = 10*log10(k);            % conversion to dB

ES_Gain = Compute_ES_Gain(f);

ES_GT = Compute_ES_GT(f, el);

SC_EIRP = Compute_SC_EIRP( SC_Power,DOFF);

Path_Loss = Compute_Path_Loss(f, Range);

DL_PtNo = SC_EIRP + ES_GT - Path_Loss - dBk ;

a = size(Link_Geom);                % determines size of link geometry
array

Array_size = a(1,1);                   % extracts number of data points
in array
```

```
Total_time = Array_size*Time_step;           % Time step selected in
STK

Time = [0:Time_step:Total_time - Time_step];  % allows for plotting vs
time

subplot(2,2,1); plot(Time,DL_PtNo,...
    'DisplayName','Time vs C/No');

title({'C/No'});
ylabel({'C/No)'});
xlabel({'Time(min)'});

subplot(2,2,2); plot(Time,el,...
    'DisplayName','Elevation vs time');

title({'Elevation'});
ylabel({'El(deg)'});
xlabel({'Time(min)'});

subplot(2,2,3); plot(Time,Range_in_Km,...
    'DisplayName','Time vs Range');

title({'Range'});
ylabel({'Range(Km)'});
xlabel({'Time(min)'});

subplot(2,2,4); plot(Time,DOFF,...
    'DisplayName','DOFF vs time');

title({'DOFF'});
ylabel({'DOFF'});
xlabel({'Time(min)'});
```

Compute Uplink Pt/No

```
function [ UL_PtNo ] = Compute_UL_PtNo(Ta, NF, ES_Power, f, Link_Geom,
Time_step);

% Computes the uplink carrier power to noise density and produces
% corresponding plots

el = Link_Geom(:,1);     % extracts elevation from the geometry array
Range = Link_Geom(:,2);  % extracts range from the geometry array
DOFF = Link_Geom(:,3);   % extracts DOFF from the geometry array

k = ((1.3806504*10^-23)); % Boltzmann's constant

dBk = 10*log10(k);            % conversion to dBk

a = size(Link_Geom);                   % determines size of geometry
array
```

```
Array_size = a(1,1);                  % extracts number of data points

Total_time = Array_size*Time_step;       % Time step selected in STK

Time = [0:Time_step:Total_time - Time_step]; % allows for plotting vs
time

Range_in_Km = Range/1000;

SC_GT = Compute_SC_GT(NF, DOFF, Ta);

ES_EIRP = Compute_ES_EIRP(ES_Power, f, Link_Geom);

Path_Loss = Compute_Path_Loss(f, Range);

UL_PtNo = ES_EIRP + SC_GT - Path_Loss - dBk;

subplot(2,2,1); plot(Time,UL_PtNo,...
    'DisplayName','Time vs C/No');

title({'C/No'});
ylabel({'C/No)'});
xlabel({'Time(min)'});

subplot(2,2,2); plot(Time,el,...
    'DisplayName','Elevation vs time');

title({'Elevation'});
ylabel({'El(deg)'});
xlabel({'Time(min)'});

subplot(2,2,3); plot(Time,Range_in_Km,...
    'DisplayName','Time vs Range');

title({'Range'});
ylabel({'Range(Km)'});
xlabel({'Time(min)'});

subplot(2,2,4); plot(Time,DOFF,...
    'DisplayName','DOFF vs time');

title({'DOFF'});
ylabel({'DOFF'});
xlabel({'Time(min)'});





end
```

Compute Earth Station EIRP

```
function [ ES_EIRP ] = Compute_ES_EIRP( ES_Power, f, Link_Geom);

% Computes Earth Station EIRP

el = Link_Geom(:,1);     % extracts elevation from the geometry array
Range = Link_Geom(:,2);  % extracts range from the geometry array
DOFF = Link_Geom(:,3);   % extracts DOFF from the geometry array

ES_Gain = Compute_ES_Gain(f);

ES_Feeder_Loss = 1;  %% assumed 13m RBC Feeder Loss

ES_PtgCntl_Loss = Compute_ES_PtgCntl_Loss();

Pol_Loss = Compute_Pol_Loss(DOFF);

ES_EIRP = ES_Power + ES_Gain - ES_PtgCntl_Loss + Pol_Loss -
ES_Feeder_Loss;


end
```

Compute Earth Station Gain

```
function [ ES_Gain ] = Compute_ES_Gain(f);

% Computes the Earth Station Gain in particular the RBC 13m antenna
gain

c = 299792458 ;  % Speed of light in m/s

ES_ap = 13; % RBC antenna diameter

eff = .668; % RBC antenna efficiency


ES_Gain = 10*log10(eff*(((pi*ES_ap*f)/c)^2)) ; % Gain in dB


end
```

Compute earth Station Gain over Temperature (G/T)

```
function [ ES_GT ] = Compute_ES_GT( f, el);

% Computes the earth station gain over temperature
```

```
ES_Gain = Compute_ES_Gain(f);

ES_Ts = Compute_ES_Ts(el);

ES_GT = ES_Gain - ES_Ts;

end
```

Compute Earth Station Pointing Control Loss

```
function [ ES_PtgCntl_Loss ] = Compute_ES_PtgCntl_Loss()

% Computes Earth Station pointing control loss. Telecom Forecaster
model
% used

HPBW = 1;   % RBC 13 meter HPBW = 1 deg
DOFF = .01; % Assume a DOFF error of .01

ES_PtgCntl_Loss = 3*(((2*DOFF)/HPBW).^2); % dB


end
```

Compute Earth Station Antenna Noise Temperature (Ta)

```
function [ ES_Ta ] = Compute_ES_Ta(el)

% Computes the earth station antenna noise temperature. 810-005
% antenna temperature model used

elrad = el*pi/180; % conversion to radians

% Below are RBC specific parameters used in this model
T1 = 19;    % system specific variable
T2 = 9;     % system specific variable
a = .05;    % system specific variable
CD = 0;     % weather dependent variable
Az = .033;  % zenith atmospheric attenuation for selected CD

ES_Ta = T1 + T2*exp(-a*el) + (255 +25*CD)*( 1 - ( 1 ./ ( 10.^(Az
./(10*sin(elrad))))));

end
```

Compute Earth Station System Noise Temperature (Ts)

```
function [ ES_Ts ] = Compute_ES_Ts(el);
```

```
% Computes the system noise temperature of the RBC system

k = ((1.3806504*10^-23)); % Boltzmann's constant

% alpha = .85;
% Tr = 105;          %Transportable RBC parameters
% To = 293;

% Parameters below are RBC specific
alpha = .85;
Tr = 33;
To = 293;

Ta = Compute_ES_Ta(el);

ES_Ts = 10*log10((Tr + alpha*Ta + (1-alpha)*To)) ;%System noise temp in
dBm


end
```

Compute Path Loss

```
function [ Path_Loss ] = Compute_Path_Loss(f, Range)

% Computes Path Loss

c = 299792458; %% in m/s

Path_Loss = 10*log10(((4*pi*Range*f)./ c).^2); % in dB


end
```

Compute Polarization Loss

```
function [ Pol_Loss] = Compute_Pol_Loss(DOFF)

% Computes Polarization Loss. Telecom Forcaster model used based on
degrees
% off boresight

Pol_Loss = .0000000138888844*(DOFF.^4) - .000338888816*(DOFF.^2) -
.000000286102295;



end
```

Compute Spacecraft EIRP

```
function [ SC_EIRP ] = Compute_SC_EIRP(SC_Power, DOFF);

% Computes the spacecraft EIRP

SC_Gain = Compute_SC_Gain(DOFF);

SC_Insertion_Loss = 5;

Pol_Loss = Compute_Pol_Loss(DOFF);

ES_PtgCntl_Loss = Compute_ES_PtgCntl_Loss();

SC_EIRP = SC_Power + SC_Gain + SC_Insertion_Loss + Pol_Loss -
ES_PtgCntl_Loss ; %in dB

end
```

Compute Spacecraft Gain

```
function [ SC_Gain ] = Compute_SC_Gain(DOFF)

% Computes the spacecraft gain. Telecom Forcaster model used based on
% degrees off boresight

SC_Gain = -.0000000190972252*(DOFF.^4) - .000409027729*(DOFF.^2) +
1.5999998; % in dB

end
```

Compute Spacecraft Gain over Temperature (G/T)

```
function [ SC_GT ] = Compute_SC_GT( NF, DOFF, Ta);

% Computes the spacecraft gain over noise temperature.

SC_Gain = Compute_SC_Gain(DOFF);

Ts = Compute_SC_Ts( Ta, NF);

SC_GT = SC_Gain - Ts; % in dB

end
```

Compute Spacecraft System Noise Temperature (Ts)

```
function [ SC_Ts ] = Compute_SC_Ts( Ta, NF);
```

```
% Computes spacecraft system noise temperature. Telecom Forecaster
%model for an Omni antenna used

k = ((1.3806504*10^-23)); % Boltzmann's constant
To = 290;

F = 10^(NF/10); % Noise Figure of spacecraft

SC_Ts = 10*log10((Ta + (F-1)*To)) ; % in dB

end
```

Compute Service Modulation Loss

```
function [ Svs_Mod_Loss ] = Compute_Svs_Mod_Loss( MI )

% MI = modulation index

Svs_Mod_Loss = 10*log10(2*besselj(1,MI)^2);

end
```

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14. ABSTRACT

The Air Force Satellite Control Network (AFSCN) is a worldwide network of ground stations that support a wide variety of users from the National Aeronautics and Space Administration (NASA) to the National Reconnaissance Office (NRO). The network performs tracking, telemetry, and commanding (TT&C) for these varied users. Users, located at Satellite Operations Centers (SOC), must compete for time on the AFSCN. This thesis demonstrates how to predict satellite link performance, specifically by users of the AFSCN. It will also demonstrate how users might use this capability to save spacecraft power. A tool was created called the AFSCN Link Predictor (LP) which predicts BER across a future contact. The design of the AFSCN LP and a proposed modification to the AFSCN using DoD Architecture Framework (DoDAF) was accomplished. A simulation, using this tool, was conducted that demonstrates the utility of performance prediction for representative low, medium, and high earth orbiting spacecraft communicating with two geographically separated ground stations.

15. SUBJECT TERMS

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